In Situ Surface Protection System
SBIR Phase I
Final Report

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Air Force Material Command
United States Air Force

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PREFACE

The work reported herein was performed by RedZone Robotics and its subcontractor, the University of Tennessee Space Institute, under a Small Business Innovation Research Phase One contract, number F40600-97-C-0005. The contract was awarded based on a proposal submitted by RedZone Robotics in response to DoD SBIR topic AF97-246, Environmentally Safe, In Situ Surface Protection of Carbon Steel Structures which seeks:

> A system for implementing laser induced surface improvements technique to extend the longevity of existing air supply ducts while meeting future air purity needs. The technique uses heat generated by the absorption of a high-powered laser beam to coalesce metallic compounds introduced at the surface of a base metal, and forms an alternate alloy with desirable characteristics in a thin surface layer.
>
> The system must include: (1) a remotely-operated robot capable of traversing the ductwork, (2) a laser beam delivery unit on the robot, and (3) an alloying element delivery unit.

Thanks is extended to the military, civilian and site contractor staffs of the Arnold Engineering Development Center for their support and assistance during this project.

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1.0 INTRODUCTION

1.1 BACKGROUND

An important mission of the Arnold Engineering Development Center is testing jet engines for military and commercial customers. An extensive network of ducting is used to direct air flow through test engines. Much of the ducting is made from low carbon steel. Rust particles generated by corrosion of the ducting may damage test engines.

The University of Tennessee Space Institute (UTSI) has developed the Laser Induced Surface Improvement (LISI) process. The LISI process uses a laser to melt a precursor and underlying substrate to form a surface layer with different properties than the substrate. UTSI is developing a LISI process application to produce a corrosion resistant surface layer on the AEDC ducting.

Access to the interior of the ducting is restricted and the size of some ducts precludes human entry or work. Robotic systems have been proposed to deliver LISI process equipment within the ducting. This effort explored the feasibility of robotic systems and defined the functional requirements for robotic systems.

1.2 OBJECTIVES

The primary objectives of the Phase One effort were to assess the feasibility of and determine the functional requirements for robotic systems to deliver the LISI process equipment in the AEDC ducting.

1.3 PROJECT TASKS

To achieve these objectives, a number of tasks were defined to develop the necessary information. The University of Tennessee Space Institute was subcontracted to assist in the completion of these tasks. Meetings were held with University of Tennessee Space Institute personnel to develop an understanding of the LISI process. Meetings were held with Arnold Engineering Development Center personnel to develop understanding of the facility, its operation, and program goals and objectives. The Fury robotic inspection system was operated in the AEDC ductwork to identify issues associated with robot operation in the ductwork. A laser end effector was mounted on the Fury robot to perform laser processing at UTSI to identify issues associated with laser operation on a robotic system. Alternative methods for dispensing the precursor were investigated. Information collected from the above tasks was used to develop a functional requirements document for a robotic surface improvement system to perform LISI processing in the ductwork at AEDC. An inspection demonstration was also performed with the Fury system gathering wall thickness information on a duct sample.

1.3.1 UTSI Kickoff Meeting Task

The goals of this task were to develop an understanding of the Laser Induced Surface Improvement (LISI) technology and finalize plans for UTSI support of other project tasks. Areas of interest included LISI process control requirements, laser system size and support requirements, alloying agent characteristics, alloy dispensing requirements, and factors affecting LISI process speed and quality.

1.3.2 AEDC Kickoff Meeting Task

The goals of this task were to develop an understanding of the AEDC Rust and Dust program, ducting geometry, sizes, shapes, obstacles and accessibility, duct problem areas and area coverage requirements, etc., finalize plans for other project tasks, and finalize project management activities.

1.3.3 Test Robot Mobility in AEDC Ducts Task

The goals of this task were to identify maneuvering strengths and weaknesses of the Fury prototype in representative AEDC ETF ducts and to develop an understanding of duct obstacles and geometry, robot access and movement challenges.

1.3.4 Breadboard Laser and Robot System Task

The goals of this task were to mount the UTSI laser optics system to the Fury robot creating a breadboard robotic surface improvement system and operate that breadboard system on test plates in the UTSI laboratory to identify system integration problems, evaluate LISI robotic deployment requirements, and demonstrate robotic LISI operation.

1.3.5 Alloy Dispenser Conceptual Design Task

The goals of this task were to identify and evaluate LISI precursor alloy dispenser designs compatible with a robotic surface protection system and select a dispensing concept.

1.3.6 Develop Functional Requirements Task

The goal of this task was to prepare a document describing the functional requirements for a robotic surface improvement system to deliver LISI process equipment.

1.3.7 Fury Inspection Demonstration Task

The goal of this task was to explore the feasibility of collecting duct condition data using a robotic system. The Fury robotic system collected wall thickness information on a section of ducting.

2.0 RESULTS

2.1 UTSI KICKOFF MEETING

The kick off meeting was held at the University of Tennessee Space Institute with representatives of RedZone Robotics and UTSI. In attendance were:

Dr. Mary Helen McCay	UTSI
Dr. John Hopkins	UTSI
Dr. Narendra Dahotre	UTSI
Fred Schwartz	UTSI
Bill Boss	UTSI
Brice Bible	UTSI
Frank Robb	RedZone Robotics
David Norton	RedZone Robotics
John Iaconis	RedZone Robotics

The SBIR Phase 1 project plan, schedule and objectives were presented and discussed. A preliminary robotic LISI system concept was presented and discussed. A draft functional requirements document was presented and discussed in detail. Plans for Task 4, Breadboard Laser and Robot System, were finalized.

The functional requirements document includes an operating scenario for a robotic LISI system. Significant discussion of the operating scenario occurred. The UTSI representatives identified concerns over how robot system operation could affect the LISI process. They also highlighted some operational and logistical issues based on their experience at AEDC.

The UTSI representatives described the characteristics of the laser system anticipated for this application including size, cost, power and cooling requirements.

2.2 AEDC KICKOFF MEETING

The project kick off meeting was held at the Arnold Engineering Development Center with representatives of the U.S. Air Force, Sverdrup Technology, University of Tennessee Space Institute and RedZone Robotics. In attendance were:

David Beale	AEDC Sverdrup Technology
Darren Kraabel	U.S. Air Force
Kevin Zysk	USAF DOT
Tom Bentley	AEDC Sverdrup Technology
Steve Dunn	AEDC Sverdrup Technology

Brice Bible	UTSI
Frank Robb	RedZone Robotics
David Norton	RedZone Robotics
John Iaconis	RedZone Robotics
Bruce Thompson	RedZone Robotics

The SBIR Phase 1 project plan, schedule and objectives were presented and discussed. A preliminary robotic LISI system concept was presented and discussed. A draft functional requirements document was presented and discussed. Plans for Task 3, Test Robot Mobility in AEDC Ducts, were finalized. Plans for the Fury Inspection Demonstration were finalized.

The functional requirements specification includes an operating scenario for a robotic LISI system. Significant discussion of the operating scenario occurred. AEDC representatives described typical testing operations and schedules and indicated the size of potential time windows for robotic LISI processing. The logistics and safety issues of opening the ducting were described.

The need to identify relevant codes and standards used by AEDC that would govern the design of a robotic LISI system was discussed to support functional requirements development. Health and safety work done for the UTSI B header demonstration was considered a good starting point.

Discussion of AEDC program requirements and goals also occurred. Duct condition assessment is needed to determine if a duct can be upgraded or should be replaced. Tools and techniques are needed for condition assessment. Structural integrity is also a concern. Various upgrading options exist. Some ducts are being painted to reduce corrosion. LISI is viewed as having significant potential as an upgrade option. AEDC has an ongoing process of prioritizing duct upgrading/replacement activities. AEDC program goals target a fully functional robotic LISI system available in mid FY99.

2.3 TEST ROBOT MOBILITY IN AEDC DUCTS

2.3.1 Test Activities

The Fury robot system equipment was unloaded from the transporting van and positioned on the lower level of the ETF. The A Header was entered through a manway. The robot was operated in the axial and circumferential directions on a cylindrical portion of the header. The robot was also operated on the surface of a spherical duct connection.

The entire length of the A Header was carefully examined. Sketches and measurements of various duct features were made. Particular attention was paid to the geometry of duct manway entry points.

The Fury robot was also inserted in the A-4 discharge duct through a manway. The robot was operated in an axial direction in the duct.

The interior of the A-4 discharge duct was examined through the manways. Human entry into the A-4 duct was not possible. Measurements of the manways were made.

Photographs of the interior of the A Header and the A-4 duct were taken.

2.3.2 Observations

Slippage was observed between the robot magnetic wheels and A Header duct wall The smooth somewhat polished surface of the magnetic wheels combined with the smooth surface of the duct produced a low coefficient of friction. The duct surface was also somewhat slippery under foot suggesting that a surface contaminant such as fine rust particles or a process liquid may be present.

The rear wheel of the Fury robot separated from the wall of the A-4 discharge duct when the robot was operating inverted. The robot was recovered from the duct by driving and pulling on the tether. The rear robot wheel is more likely to separate from the wall due to the separating force produced by the cantilevered cleaning/UT sled. The wheel compliance travel of the Fury robot may have been used when steering on the relatively small diameter of the A 4 duct resulting in the magnetic wheel being pried from the duct wall.

Some difficulty was encountered in moving over the butt weld beads. This was also a friction problem. The Fury robot can move over the lap joints used in fabricating underground petroleum storage tanks.

A much better understanding of duct geometry and characteristics was achieved. The potential for operational difficulties and equipment positioning problems with a robotic LISI system in the congested ETF facility was also highlighted.

2.4 BREADBOARD LASER AND ROBOT SYSTEM

A UTSI laser optics head was mounted to a bracket attached to the Fury robot. The laser fiber optic cable and process gas supply were routed. UTSI had done some development of LISI process parameters for the Fury robot speed of 2.4 in./sec. UTSI had also applied precursor to a large steel plate for breadboard testing.

Precursor lasing passes were made to adjust LISI laser process parameters. Lasing was occurring within two hours of arriving at UTSI.

Multiple precursor lasing passes were made. The steering system backlash of the Fury robot made it impossible to make multiple overlapping lasing passes. UTSI subsequently performed metallurgical analysis of the robotically lased plate. The

analysis indicated that the surface alloy composition and thickness were within desired limits.

The Fury robot magnetic wheels were driven over a LISI processed sample to determine if the LISI surface was damaged. Slight scratching of the LISI surface was observed. Magnification was needed to see more than a change in surface reflective properties.

The Fury robot magnetic wheels were driven over the unfused precursor to determine if the precursor would be removed by the wheels. The precursor remained intact. Under magnification, the magnetic wheels appeared to have flattened asperities in the precursor surface giving a smoother finish to the precursor. The magnetic wheels also appeared to track some dirt onto the precursor and imbedded the dirt in the precursor.

Information on the Hobart laser and the AEDC ducting was supplied by UTSI.

Plans for additional LISI process development at UTSI for the AEDC ducting application were discussed.

Three RedZone supplied precursor sample plates were laser processed. The samples were intended to explore the possibility of using thermal spraying to apply the precursor material. No effort was made to optimize process parameters. Evaluation of the samples was made qualitatively. The samples showed some potential for thermal spraying as a method for applying precursor. One sample plate thermal sprayed with aluminum showed some interesting results.

2.5 ALLOY DISPENSER CONCEPTUAL DESIGN

2.5.1 Alloy Dispenser Concept Selection Criteria

Criteria were developed to evaluate alternate methods for applying the LISI precursor material. The criteria were:

1. "Drying" time. How much time must elapse between the application of the precursor material and laser processing? How much time must elapse between precursor application and movement of the robot or the tether over the precursor without affecting the precursor layer?

2. Thickness control. The thickness of the precursor layer must be carefully controlled to achieve the desired surface alloy composition. Current spraying methods require multiple coats. Would the alternative method simplify the control of precursor thickness?

3. Over spray control. Over spray results in additional cleanup requirements and produces variations in precursor thickness. Would the alternative method reduce over spray?

4. Application equipment size. Space for precursor application equipment in the robot is limited. Compact precursor application equipment would be desirable.

2.5.2 Concept Generation and Selection

A brainstorming session was held to generate a list of possible precursor application methods. Over 50 ideas were produced. The brainstorming precursor dispensing ideas are shown in Appendix A.

The most promising precursor application ideas were selected from the brainstorming list. Ideas were selected based on their potential to satisfy the selection criteria. All offered rapid "drying" time and the potential for single pass application of the desired precursor layer thickness. The adhesive based ideas offered over spray control. The precursor application ideas selected were:

Thermal spray

UV cure adhesives

Hot melt adhesives

Adhesive tapes

Wax

Rubber Cement

2.5.3 Concept Evaluation

Experiments were conducted to evaluate the feasibility of the selected precursor application ideas. Thermal spray samples were obtained. Different adhesives and steel powder were purchased for experimentation. The steel powder was used to simulate the metallic alloying materials in the precursor. In house experiments focused on mixing, spreading and adhesion of the simulated precursors.

Initial experiments showed that the desired 80% metal solids in the precursor layer could not be achieved with the adhesive based approaches. Adhesive mixtures at that concentration were unworkable. Subsequent experiments were conducted at 60% metal solids concentration (by weight). The experimental results are described in Appendix B.

2.5.4 Conclusion

Thermal spray is the most promising alternative to the spraying process being developed by UTSI. It can apply the desired precursor thickness in a single pass. The "drying" time is negligible. No binder is required giving a precursor layer containing 100% metal solids. No solvents (VOC's) are needed. The precursor supply will be easier to manage. With wire feed thermal spray, no mixing of the precursor is required. Thermal spray is a commercially available process so minimum development should be required.

Additional thermal sprayed test samples have been ordered and sent to UTSI for evaluation.

2.6 DEVELOP FUNCTIONAL REQUIREMENTS

A functional requirements document was prepared. The document describes the functional requirements for a robotic system to deliver LISI process equipment in ducts at the Arnold Engineering Development Center. System and subsystem requirements were identified and quantified where possible.

The functional requirements document was developed based on discussions with representatives of the University of Tennessee Space Institute, developers of the LISI process, and representatives of the Arnold Engineering Development Center. The University of Tennessee Space Institute and the Arnold Engineering Development Center were visited to gain a first hand understanding of the LISI process and the AEDC facility. Drafts of the functional requirements documents were distributed to those representatives for review and comment.

The functional requirements document is expected to serve as the basis for system and subsystem design specifications for a robotic surface improvement system. The current functional requirements document is contained in Appendix C.

2.7 FURY INSPECTION DEMONSTRATION

2.7.1 Demonstration Plan

The Fury robotic inspection system has been developed to inspect underground petroleum storage tanks. It collects tank wall thickness measurements using an ultrasonic measuring system. An internal navigation system is used to define the approximate location of each wall thickness measurement.

The Fury robotic inspection system was operated on a section of ductwork in the AEDC scrap yard. The duct wall thickness was slightly greater than the 0.375 in. maximum wall thickness encountered in underground storage tanks. Part of the duct interior had been painted. Electrical power was supplied by a generator.

2.7.1.1 Comparative Measurements

A series of wall thickness measurements were made with the Fury system and the position of those measurements marked on the duct wall. Independent measurements of wall thickness at the same locations were subsequently made by AEDC personnel.

2.7.1.2 Wall Thickness Scan

A small wall thickness scan was performed. The normal operation of the Fury system is to collect a random sampling of the wall thickness of the tank by taking wall thickness readings as the robot moves over the tank surfaces. Data files containing hundreds of thousands of wall thickness readings are easily produced. Various data analysis and reduction techniques are applied to the wall thickness data sets to make a determination of tank condition. This approach allows pitting corrosion to be assessed without performing a 100% area coverage inspection of the tank.

A much smaller wall thickness scan was performed to illustrate the potential of robotic inspection for AEDC duct condition assessment. The robot was driven from one end of the duct to the other while automatically taking wall thickness measurements.

2.7.2 Demonstration Results

Mobility of the Fury robot was demonstrated by driving on the bottom, sides and top of the duct.

2.7.1.1 Comparative Measurements

The Fury wall thickness measurements are shown in Table 1. The comparative measurements were not available to incorporate in this report.

2.7.1.2 Wall Thickness Scan

A sample from the wall thickness position coordinate data file is in Appendix D. The data file co-ordinate system origin is located at the flange of the unpainted end of the duct section. Positive "Z" points toward the painted end of the duct. A complete description of the data file parameters is contained in Appendix E.

2.7.3 Discussion of Results

The results of the inspection demonstration were encouraging. It was possible to ultrasonically measure the duct wall thickness in spite of the rough duct interior surface. The measurements were made with an ultrasonic system developed around a different inspection application where the wall surface facing the transducer is relatively smooth and the back wall is relatively rough. Mobility of a magnetic wheeled robot over the duct surface was also demonstrated.

2.7.3.1 Comparative Measurements

Three possible sources of variation between the comparative wall thickness readings have been identified. First, a check of ultrasonic calibration at the conclusion of the Fury wall thickness measurements showed a reading 0.008 in. larger than the calibration plate thickness. This would suggest that the actual duct wall thickness is slightly less than the measured thickness. Ordinarily, less calibration drift occurs. Second, the precise center of the Fury ultrasonic transducer was not be marked on the duct wall. The heavily corroded sample duct surface means that the wall thickness varies significantly with small movements over the surface. Some variation between the manual wall thickness measurements and the Fury system measurements may be due to not measuring the wall thickness at precisely the same location. Third, a contact transducer wall thickness measurement system was used by AEDC personnel. Accurate wall thickness measurements depend on the transducer face being in contact with the wall. The heavily corroded duct surface may result in high point contact by the transducer. Ultrasonic coupling can be maintained with a thick couplant but, the reported wall thickness will be larger than the actual wall thickness.

2.7.3.2 Wall Thickness Scan

The enclosed data file shows not all wall thickness reading attempts were successful. Only one wall thickness measurement attempt is made at each location. The wall thickness is calculated by the ultrasonic system based on predefined measurement gates. A strong, low noise ultrasonic signal properly located in the measurement gates is needed for successful wall thickness determination. The irregular interior surface of the duct makes it more difficult to achieve a strong, low noise signal.

2.7.4 Potential Measurement Improvements

Several methods of improving ultrasonic system measurement performance have been identified.

Some wall thickness measurements are missed due to processing speed limitations of the current ultrasonic equipment. The current equipment uses a 486 based PC. A higher speed platform would resolve this problem. Making fewer measurement attempts per second by not overlapping the ultrasonic pulses or using a larger diameter ultrasonic transducer would also resolve this problem.

Some wall thickness readings are missed when coupling is lost between the ultrasonic transducer and the duct wall. Any air between the transducer and duct wall attenuates the ultrasonic signal. Increasing the couplant flow rate and/or improving sealing between the transducer mounting block and the duct wall should help to maintain coupling to the irregular duct wall. A higher viscosity couplant could also help although it presents other problems with cleanup, pumping and, possibly, bubbles.

Some wall thickness readings are missed when the duct wall surface is not parallel to the face of the ultrasonic transducer. The ultrasonic pulse and wall surface behave like a light beam and mirror. If the duct surface is not parallel to the transducer face, only part of the reflected ultrasonic pulse will reach the transducer resulting in a weak or nonexistent signal. The irregular, pitted surface of the duct wall would produce this effect. A larger diameter ultrasonic transducer at the same spacing from the wall would make it more likely that the reflected ultrasonic pulse would reach the transducer. A larger diameter ultrasonic transducer would make it more difficult to detect small diameter pits.

Some wall thickness readings are missed because the ultrasonic signal does not fall into the predetermined wall thickness measurement gates. It may be possible to adjust gate parameters to increase the percentage of successful wall thickness readings.

3.0 CONCLUSIONS

A good understanding of the functional requirements for a robotic surface improvement system was developed through the onsite kick off meetings at AEDC and UTSI as well as the robot mobility testing and LISI breadboard testing done with the Fury system. This understanding led to a functional requirements document for a robotic surface improvement system.

Analysis of the functional requirements leads to the conclusion that a robotic system is a feasible method of delivering LISI process equipment inside the ducts. A tethered magnetic wheeled robot with interchangeable LISI process payloads would be capable of delivering the LISI equipment over a significant portion of the AEDC ducting. Figure 1 shows an artist's rendering of the robotic surface improvement system. Figure 2 shows the robot assembly.

The Fury inspection demonstration showed the potential of robotic systems to obtain duct condition inspection data. The interchangeable payload feature of the robotic surface improvement system concept would allow this same system to deliver duct inspection payloads.

Finally, precursor application methods were explored and thermal spraying was viewed as the most promising alternative to the precursor application methods being developed by UTSI. Thermal spraying offers very fast "drying" times with no release of vapors and provides a precursor layer containing 100% metal solids.

4.0 ILLUSTRATIONS

Figure 1. Robotic Surface Improvement System

Figure 2. Robot Assembly

5.0 TABLES

Table 1. Fury Wall Thickness Measurements

Position No.	Wall Thickness, in.
1	0.412
2	0.409
3	0.423
4	0.408
5	0.401
6	0.422
7	0.415
8	0.398
9	0.390
10	0.374
11	0.386
12	0.393
13	0.394
14	0.375

6.0 APPENDICES

APPENDIX A: PRECURSOR DISPENSING IDEAS

adhesive
UV cure adhesive
hot melt adhesive
spread with knife
squeegee
paste
apply like asphalt paving machine
brazing pastes
soldering creams
wax substance suspend in wax
laser on low power to melt hot melt adhesive
spray
- airless
- air
- two part
- multipart
- RIM molding head
- electrostatic

tape
adhesive tape
transfer tape
metal tape
- tack weld
- spot weld

power roller tape dispenser
heat dry
roller
Wagner power roller
dribble out through robot wheels
blow precursor into laser beam
thermal spray into laser beam
wire or tape feed into laser bean (MIG welder)
puddles
flood duct with precursor
controlled floating (soap scum)
paint balls
anti seeze- spreads everywhere
zero surface tension fluid
super fluid
brush on

big felt tip marker
contoured sheets lay in and fuse
contoured film lay in and fuse
do a liner
shape memory alloy preform
inflate a liner
optical plate holds precursor in place lase through optical plate
atomize and blow into duct
    roach bomb
    turn on compressors
thermal spray
electroplating
electroplating pen
plasma spray
mix with magnetic material
electrostatically
powder coat
explosive process
detonation gun
sputtering
chemical vapor deposition
Apply precursor as gas, liquid, semi solid, solid, powder
Apply precursor by spraying, brushing, rolling, troweling, condensing, overlaying

APPENDIX B: PRECURSOR DISPENSING EXPERIMENTAL REPORT

Date: 25 April, 1997
Name: Troy D. Lehman
Subject: 96068 Alloy Precursor Dispenser Development
Sent to: Frank Robb

Objective

Experiments conducted to explore the feasibility of alternative materials for suspending, and methods of applying to steel, University of Tennessee Space Institute's proprietary precursor material. UTSI currently employs a paint spray gun for the precursor application.

Summary

Four main areas of focus were identified for these trials: Ease of mixing and application, mixture work life, adhesion to the steel, and ability to control the thickness of the precursor material. UTSI has indicated that the precursor is 80% (by weight) metal and must be applied at a thickness of .008". Indogrit metal powder was used to simulate the characteristics and properties of the metal content of the UTSI precursor and was mixed with and/or applied to selected adhesives, tapes, and waxes. This was applied to cold rolled steel plate via a plastic putty knife riding on stainless shim stock as thickness guides. Coverage areas all measured approximately 5 inches by 1.5 inches. The only steel plate preparation performed was a quick wipe with a shop rag. There were several UV cured adhesives used in the test. Lacking the specified UV source, we attempted to cure the adhesives with a 1970's vintage sun lamp which did not work very well. There are no UV output specifications on the lamp and it produces radiant heat.

Note: The preparations containing 80 percent metal powder proved impossible to mix and spread, so the metal powder content was reduced to 60 percent for the tests.

Discussion

Devcon 5 Minute Epoxy:

Mixes easily, good consistency, spreads smoothly, adheres to steel very well.

Cures very quickly. Very short work life after mixing. Started to clump while spreading within a minute.

Using .008" guides, post cure thickness measured .016" ±.001".

Phenoseal Liquid Caulk:

Mixes very easily, spreads smoothly, adheres to steel well. Very thin consistency.

Cures very slowly. Starts to "skin" at 20 minutes. Manufacturer specifies 6 to 24 hours for full cure. Caused oxidation of metal powder.

Using .008" guides, post cure thickness measured .004" ±.001".

Sanford Rubber Cement:

Mixes easily, good consistency, spreads smoothly, adheres to steel well.

Mixture cures approximately 20 minutes after application to steel. Curiously, unused portion remained usable for about an hour and a half.

Using .010" guides, post cure thickness measured .004" ±.001".

Loctite Impruv® #366 UV cured adhesive

Starts to cure almost immediately after mixing with metal powder (no primer). Loctite technicians suspect this may be caused by the metal powder reacting with the acrylic acid in the adhesive. It is not spreadable after mixing completely.

Applied the adhesive only to the steel plate. It started to "tack" under the sun lamp in approximately 1 hour at a distance from the source of 3.5 inches.

Applied adhesive only to the steel plate and heated it to about the same temperature as the sample under the lamp. This set up in approximately 1 hour 45 minutes.

Applied adhesive to steel and then dusted it with metal powder. This started to set up in 20 minutes. However, because the powder did not settle to the bottom layer of the adhesive, it did not adhere to the steel plate well.

Loctite Speedbonder™ #325 activator cured adhesive

Mixes easily, good consistency, spreads smoothly. Also contains acrylic acid, but did not cure prematurely after mixing with metal powder. Apparently it is cured only by the activator. Sample was still usable after 24 hours.

Performed two different application runs. The first with activator sprayed onto plate prior to spreading precursor mixture, the second with activator sprayed both on the plate and then on top of precursor mixture. Neither cured completely or adhered to steel.

Loctite Litetak® #3751 low intensity UV cured adhesive:

Mixes easily, good consistency, spreads smoothly, adheres to steel well. No problem with premature curing. Sample remained usable for about 6 hours.

Cures under sun lamp in approximately 1 hour.

Heat only cures in approximately 1.5 hours.

Using .010" guides, post cure thickness measured .005" ±.001".

Clear, all purpose glue stick:

Very sticky after melting. Too sticky to mix well or apply to steel smoothly, although it does adhere to the steel plate pretty well.

Peel Coat Stripable Wax:

Melts at approximately 200° F, but is easier to mix at ~325° F (flash point is 395° F, so I didn't want to go too hot).

Mixes easily, good consistency.

Re-solidifies as soon as it contacts room temperature spreader or steel plate, rendering it unspreadable. Does not adhere to steel well. Performed three more runs as follows:

1. <u>Heated spreader</u>:

Heated a stainless steel spreader to ~160° F and had better results. Spreads, but not smoothly. Spreader cools quickly so the "spreading window" is less than 1 minute. Still does not adhere to steel well.

Rough surface finish. Using .010" guides, thickness measured .010" ±.005".

2. <u>Heated spreader and plate:</u>

Heated both the spreader and the steel plate to ~160° F and got better results still. Spreader and steel both cool quickly, but the mixture spreads much more smoothly and adheres to the steel well.

Using .010" guides, thickness measured .013" ±.001".

3. <u>Glue gun and heated spreader</u>:

Made an aluminum spreader attachment for the glue gun which remains in contact with the gun heating element, heating it to the same temperature (~380° F). Made metal powder and wax "glue sticks" by pouring mixture into rolled UHMW, which I then loaded into the glue gun.

Wax is kept hot by the spreader and flows freely and spreads smoothly. Adheres to Using .010" guides, thickness measured .013" ±.001".

Peel Coat wax/clear glue combination:

Combined metal powder with equal part wax and glue. Able to mix it thoroughly, but it's a sticky mess.

Acts about the same as wax-only mixture with only a marginal improvement in adhesion.

Machinable wax:

Very similar to Peel Coat, but not as pliable. Melts at a higher temperature (~400° F). Re-solidifies even faster on room temperature plate than the Peel Coat, so does not spread smoothly.

Does not adhere to steel; curls up as it cools and becomes brittle.

Pre-heating spreader and steel plate does not help.

3M #665 double side adhesive tape:

Placed a strip between .010" guides and applied dry metal powder. Only a very thin dusting of metal powder stuck.

Tape adheres to steel plate very well.

3M #665 tape with Phenoseal caulk/metal powder coating:

Placed tape (with liner) between guides, spread the caulk/metal powder mixture onto it, and let it cure.

Mixture spreads easily onto tape and adheres to it well. Caulk does not crack or peel off after cure, even while rolling and twisting tape.

Using .025" guides, post cure thickness (minus tape and liner) measured .008" ±.001".

Conclusion

As stated in the summary, the 80 : 20 mixtures (metal powder : adhesive) proved too dry to spread. If the metal content of UTSI's precursor must be 80%, then none of the adhesive substances used during this test look very promising as a medium to adhere the metal powder to steel. That notwithstanding, some of the tests yielded interesting results and may warrant further investigation as viable alternatives to spray application. Three in particular stand out: Loctite Litetak® UV cure adhesive (would require proper UV source for definitive test), Peel Coat/glue stick/heated applicator trio, and the 3M #665 tape/ Phenoseal Caulk combination.

In looking at the measured thicknesses, it is obvious that the combination of different material characteristics and human error (i.e. spreader angle and pressure) leads to big variations of post cure precursor material thickness. This would probably be easily overcome with practice and more accurate spreader fixturing.

APPENDIX C: FUNCTIONAL REQUIREMENTS DOCUMENT

APPENDIX D: FURY INSPECTION DATA FILE SAMPLE

```
Project Date :      03-21-1997
UT FILE :    C:\FURY\21MARCHT.CSV
Company :     AEDC
Address :    Tulahoma TN
Phone   :
Diameter :   4.83333
Length :     25.00000

<***************************************************************>
12:38:24 WALL  0000072.34  0000012.93  0004.3 -00000001 00000672   ***  ""
12:38:24 WALL  0000072.10  0000012.95  0003.7 -00000001 00000673   ***  ""
12:38:25 WALL  0000072.40  0000012.96  0004.2 -00000001 00000674   ***  0.4157
12:38:25 WALL  0000072.08  0000012.98  0003.6 -00000001 00000675   ***  ""
12:38:25 WALL  0000072.52  0000013.00  0004.3 -00000001 00000676   ***  0.4111
12:38:25 WALL  0000071.85  0000013.01  0003.6 -00000001 00000677   ***  ""
12:38:25 WALL  0000072.41  0000013.03  0004.0 -00000001 00000678   ***  0.4076
12:38:25 WALL  0000071.96  0000013.04  0003.7 -00000001 00000679   ***  0.4215
12:38:25 WALL  0000072.47  0000013.06  0003.3 -00000001 00000680   ***  ""
12:38:25 WALL  0000072.13  0000013.07  0004.5 -00000001 00000681   ***  ""
12:38:25 WALL  0000072.28  0000013.09  0003.3 -00000001 00000682   ***  ""
12:38:25 WALL  0000072.41  0000013.11  0003.0 -00000001 00000683   ***  0.4250
12:38:25 WALL  0000072.41  0000013.12  0004.0 -00000001 00000684   ***  ""
12:38:26 WALL  0000072.14  0000013.14  0003.7 -00000001 00000685   ***  0.4343
12:38:26 WALL  0000072.41  0000013.16  0003.3 -00000001 00000686   ***  0.4157
12:38:26 WALL  0000072.08  0000013.17  0003.7 -00000001 00000687   ***  ""
12:38:26 WALL  0000072.08  0000013.19  0003.5 -00000001 00000688   ***  0.4285
12:38:26 WALL  0000071.84  0000013.20  0003.5 -00000001 00000689   ***  ""
12:38:26 WALL  0000071.98  0000013.22  0003.8 -00000001 00000690   ***  0.4180
12:38:26 WALL  0000071.61  0000013.24  0002.8 -00000001 00000691   ***  0.4389
12:38:26 WALL  0000072.18  0000013.25  0003.7 -00000001 00000692   ***  0.4227
12:38:26 WALL  0000072.04  0000013.27  0003.3 -00000001 00000693   ***  ""
12:38:26 WALL  0000072.22  0000013.28  0004.0 -00000001 00000694   ***  0.4169
12:38:26 WALL  0000072.02  0000013.30  0002.9 -00000001 00000695   ***  0.4146
12:38:27 WALL  0000072.60  0000013.32  0003.5 -00000001 00000696   ***  0.4238
12:38:27 WALL  0000072.14  0000013.33  0003.6 -00000001 00000697   ***  ""
12:38:27 WALL  0000072.27  0000013.35  0003.3 -00000001 00000698   ***  0.4273
12:38:27 WALL  0000072.03  0000013.36  0003.2 -00000001 00000699   ***  ""
12:38:27 WALL  0000072.09  0000013.38  0003.0 -00000001 00000700   ***  ""
12:38:27 WALL  0000071.90  0000013.40  0003.7 -00000001 00000701   ***  ""
12:38:27 WALL  0000071.97  0000013.41  0002.6 -00000001 00000702   ***  ""
12:38:27 WALL  0000072.06  0000013.43  0003.5 -00000001 00000703   ***  0.4134
12:38:27 WALL  0000071.98  0000013.44  0002.8 -00000001 00000704   ***  ""
12:38:28 WALL  0000072.01  0000013.46  0003.2 -00000001 00000705   ***  0.4122
```

12:38:28	WALL	0000071.93	0000013.48	0003.2	-00000001	00000706	***	""
12:38:28	WALL	0000072.06	0000013.49	0003.3	-00000001	00000707	***	0.4250
12:38:28	WALL	0000071.73	0000013.51	0003.8	-00000001	00000708	***	""
12:38:28	WALL	0000071.78	0000013.53	0001.6	-00000001	00000709	***	0.4065
12:38:28	WALL	0000072.15	0000013.54	0003.1	-00000001	00000710	***	""
12:38:28	WALL	0000071.61	0000013.56	0003.4	-00000001	00000711	***	0.4285
12:38:28	WALL	0000072.09	0000013.57	0003.2	-00000001	00000712	***	0.1911
12:38:28	WALL	0000071.41	0000013.59	0003.0	-00000001	00000713	***	0.4227
12:38:28	WALL	0000071.83	0000013.61	0002.3	-00000001	00000714	***	""
12:38:29	WALL	0000071.80	0000013.62	0003.2	-00000001	00000715	***	0.4354
12:38:29	WALL	0000071.77	0000013.64	0003.3	-00000001	00000716	***	""
12:38:29	WALL	0000071.46	0000013.65	0002.7	-00000001	00000717	***	""
12:38:29	WALL	0000072.10	0000013.67	0002.7	-00000001	00000718	***	""
12:38:29	WALL	0000071.66	0000013.69	0003.0	-00000001	00000719	***	""
12:38:29	WALL	0000071.71	0000013.70	0002.6	-00000001	00000720	***	""
12:38:29	WALL	0000071.44	0000013.72	0002.9	-00000001	00000721	***	""
12:38:29	WALL	0000071.63	0000013.74	0002.5	-00000001	00000722	***	0.4041
12:38:29	WALL	0000071.65	0000013.75	0003.4	-00000001	00000723	***	""
12:38:29	WALL	0000071.22	0000013.77	0003.3	-00000001	00000724	***	0.4238
12:38:29	WALL	0000071.25	0000013.78	0002.1	-00000001	00000725	***	""
12:38:30	WALL	0000071.21	0000013.80	0001.5	-00000001	00000726	***	0.4215
12:38:30	WALL	0000071.16	0000013.82	0001.4	-00000001	00000727	***	""
12:38:30	WALL	0000072.23	0000013.83	0002.6	-00000001	00000728	***	""
12:38:30	WALL	0000071.32	0000013.85	0002.7	-00000001	00000729	***	""
12:38:30	WALL	0000071.84	0000013.87	0003.1	-00000001	00000730	***	0.4261
12:38:30	WALL	0000071.76	0000013.88	0002.4	-00000001	00000731	***	""
12:38:30	WALL	0000071.86	0000013.90	0002.9	-00000001	00000732	***	0.4169
12:38:30	WALL	0000071.54	0000013.91	0002.3	-00000001	00000733	***	0.4146
12:38:30	WALL	0000071.58	0000013.93	0002.2	-00000001	00000734	***	0.4285
12:38:30	WALL	0000071.49	0000013.94	0002.8	-00000001	00000735	***	0.4169
12:38:30	WALL	0000071.46	0000013.96	0003.5	-00000001	00000736	***	0.4030
12:38:31	WALL	0000071.41	0000013.98	0001.9	-00000001	00000737	***	0.4296
12:38:31	WALL	0000071.79	0000013.99	0003.0	-00000001	00000738	***	0.4157
12:38:31	WALL	0000072.51	0000014.01	0000.4	-00000001	00000739	***	""
12:38:31	WALL	0000071.93	0000014.03	0002.8	-00000001	00000740	***	0.4146
12:38:31	WALL	0000071.97	0000014.04	0002.5	-00000001	00000741	***	0.4088
12:38:31	WALL	0000071.76	0000014.06	0002.6	-00000001	00000742	***	0.4204
12:38:31	WALL	0000071.93	0000014.07	0001.6	-00000001	00000743	***	""
12:38:31	WALL	0000071.96	0000014.09	0002.5	-00000001	00000744	***	0.4180
12:38:31	WALL	0000071.59	0000014.11	0001.7	-00000001	00000745	***	0.4088
12:38:31	WALL	0000071.63	0000014.12	0002.4	-00000001	00000746	***	0.4238
12:38:31	WALL	0000071.00	0000014.14	0002.0	-00000001	00000747	***	0.4146
12:38:32	WALL	0000071.43	0000014.15	0002.4	-00000001	00000748	***	0.4273
12:38:32	WALL	0000071.15	0000014.17	0001.8	-00000001	00000749	***	""
12:38:32	WALL	0000071.46	0000014.19	0002.3	-00000001	00000750	***	""
12:38:32	WALL	0000071.27	0000014.20	0001.7	-00000001	00000751	***	0.4285

12:38:32	WALL	0000071.20	0000014.20	0003.1	-00000001	00000752	***	0.4424
12:38:32	WALL	0000071.17	0000014.22	0001.1	-00000001	00000753	***	""
12:38:32	WALL	0000071.33	0000014.23	0001.4	-00000001	00000754	***	0.4192
12:38:32	WALL	0000071.36	0000014.25	0002.2	-00000001	00000755	***	""
12:38:32	WALL	0000071.12	0000014.27	0001.8	-00000001	00000756	***	""
12:38:33	WALL	0000070.96	0000014.29	0002.3	-00000001	00000757	***	0.4308
12:38:33	WALL	0000071.14	0000014.30	0001.8	-00000001	00000758	***	""
12:38:33	WALL	0000071.10	0000014.32	0002.0	-00000001	00000759	***	0.4238
12:38:33	WALL	0000071.19	0000014.34	0001.8	-00000001	00000760	***	""
12:38:33	WALL	0000070.97	0000014.35	0001.7	-00000001	00000761	***	0.4308
12:38:33	WALL	0000071.36	0000014.37	0001.4	-00000001	00000762	***	""
12:38:33	WALL	0000071.19	0000014.38	0001.9	-00000001	00000763	***	0.4076
12:38:33	WALL	0000071.52	0000014.40	0001.8	-00000001	00000764	***	""
12:38:33	WALL	0000071.19	0000014.42	0001.8	-00000001	00000765	***	0.4099
12:38:33	WALL	0000071.56	0000014.43	0001.3	-00000001	00000766	***	""
12:38:34	WALL	0000071.47	0000014.45	0002.0	-00000001	00000767	***	0.4447
12:38:34	WALL	0000070.92	0000014.47	0001.6	-00000001	00000768	***	""
12:38:34	WALL	0000071.54	0000014.48	0001.7	-00000001	00000769	***	0.4088
12:38:34	WALL	0000070.98	0000014.50	0001.7	-00000001	00000770	***	""
12:38:34	WALL	0000071.19	0000014.51	0001.3	-00000001	00000771	***	""
12:38:34	WALL	0000071.43	0000014.53	0002.2	-00000001	00000772	***	0.4366
12:38:34	WALL	0000071.04	0000014.55	0001.1	-00000001	00000773	***	""
12:38:34	WALL	0000071.66	0000014.56	0001.7	-00000001	00000774	***	""
12:38:34	WALL	0000071.16	0000014.58	0001.6	-00000001	00000775	***	""
12:38:34	WALL	0000071.44	0000014.60	0001.5	-00000001	00000776	***	""
12:38:34	WALL	0000071.18	0000014.61	0001.3	-00000001	00000777	***	0.4088
12:38:34	WALL	0000071.28	0000014.63	0001.7	-00000001	00000778	***	""
12:38:35	WALL	0000071.52	0000014.64	0001.4	-00000001	00000779	***	0.4250
12:38:35	WALL	0000071.56	0000014.66	0001.1	-00000001	00000780	***	""
12:38:35	WALL	0000071.46	0000014.68	0001.6	-00000001	00000781	***	""
12:38:35	WALL	0000071.72	0000014.69	0001.0	-00000001	00000782	***	""
12:38:35	WALL	0000071.53	0000014.71	0001.7	-00000001	00000783	***	0.1563
12:38:35	WALL	0000071.76	0000014.72	0000.9	-00000001	00000784	***	""
12:38:35	WALL	0000071.55	0000014.74	0001.9	-00000001	00000785	***	""
12:38:35	WALL	0000071.63	0000014.76	0001.1	-00000001	00000786	***	""
12:38:35	WALL	0000071.49	0000014.77	0000.6	-00000001	00000787	***	""
12:38:35	WALL	0000071.53	0000014.79	0001.3	-00000001	00000788	***	""
12:38:36	WALL	0000071.53	0000014.81	0001.5	-00000001	00000789	***	""
12:38:36	WALL	0000071.20	0000014.82	0001.5	-00000001	00000790	***	""
12:38:36	WALL	0000071.18	0000014.84	0000.4	-00000001	00000791	***	0.2571
12:38:36	WALL	0000071.33	0000014.85	0001.7	-00000001	00000792	***	""
12:38:36	WALL	0000070.96	0000014.87	0001.1	-00000001	00000793	***	""
12:38:36	WALL	0000071.26	0000014.89	0001.4	-00000001	00000794	***	""
12:38:36	WALL	0000070.98	0000014.90	0000.8	-00000001	00000795	***	""

APPENDIX E: FURY INSPECTION DATA FILE PARAMETER DESCRIPTION

The data file columns are as follows:

Time	- The time the data point was taken
Section	- The tank section (WALL, NEAR_ENDCAP, FAR_ENDCAP)
Robot coordinate pair	- (Phi, Z) for wall Phi in degrees, Z in feet
Theta	- The robot heading (see below).
Position.Scan	- This column is -1 if UT scanning was on for this point, otherwise it is 0.
Measurement number	- Ignore this column. It is a measurement sequence number used to synchronize scan data with position data.
***	- Three asterisks. Ignore these, they merely indicate that this data point has been combined with the UT data.
Wall Thickness	- The wall thickness at this position (if applicable) or two quotation marks ("") if there was no UT data available.

The wall coordinates (Phi, Z) + Theta are defined as follows:

The robot's position on the wall is uniquely determined by two cylindrical coordinates (Z and phi) plus an orientation (theta). The Z axis runs parallel to the principle axis of the duct from Z=0 to the far end (Z=tank length). Phi is the angular coordinate around the tank circumference. The bottom of the tank wall is where phi = 0.0, and the top of the wall is where phi = +/- 180 degrees. As you view the tank along the positive Z axis (i.e., from the near end to the far end) the left side of the tank will have negative phi coordinates, and the right side will have positive phi coordinates. Theta (the robot heading) gives the orientation of the robot's body on the tank walls. On the interior wall surfaces, theta is defined with respect to the Z axis: theta = 0.0 when the robot is aligned with the Z axis (heading toward the far endcap). When looking down on the tank, theta becomes increasingly positive as the robot is rotated counter clockwise away from the Z axis; theta becomes increasingly negative as the robot is rotated clockwise from the Z axis.